SPACE SCIENCES LABORATORY

"Distribution of this document is unlimited."

UNIVERSITY OF CALIFORNIA

BERKELEY, CALIFORNIA

This work was supported in part by the Office of Naval Research under Contract Nonr-3656(26)

This work was supported in part by the Office of Naval Research under Contract Nonr-3656(26)

Space Sciences Laboratory
University of California
Berkeley, California 94720

On the Origin of the Solar System*

H. Alfvén

Technical Report on
ONR Contract Nonr 3656(26)
Project No. NR 021 101

Partial support from NASA Grants
NsG 243 and NGR 05-003-230

Series No. 8, Issue No. 105

* A series of three lectures delivered at the Space Sciences Laboratory Colloquium, University of California, Berkeley, November, 1967.

ON THE ORIGIN OF THE SOLAR SYSTEM

Hannes Alfvén
Department of Plasma Physics
The Royal Institute of Technology
Stockholm, Sweden

I. Introduction and General Principles

1. Introduction

In his famous treatise "Leçons sur les hypothèses cosmogoniques," Henri Poincaré in 1911 gave a survey of the most important hypotheses about the origin of the solar system. The total number he listed was about half a dozen. Today the number has increased by perhaps one order of magnitude. In fact, we may say about this famous problem--with a slight travesty of Byron

We want a theory. An uncommon want
When every year and month sends forth a new one
Till after cloying the gazettes with cant
The age discovers it is not the true one.

I am not going to give a survey of the many ingenious ideas which have been suggested. Instead I should like to point out that since the time of Poincaré the general background of the problem has changed in several ways.

The problem was earlier treated by Newton mechanics and hydrodynamics. The Laplace theory belonged to this field and so did the tidal theories. However, it is now admitted by most workers in the field that magnetohydrodynamic effects were essential for the birth of the planets and satellites. This change in the theoretical background is the first important new feature.

As the second one we should list that space research has given much more experimental knowledge about the behavior of magnetized plasmas in our neighborhood. Admittedly, when the solar system was formed, conditions in space differed from present conditions in several respects. Still, many results pertaining to present conditions are applicable to the cosmogonic problem. To this should be added, that thermonuclear research has increased our knowledge of the physics of magnetized plasmas in a general way which is useful to the cosmogonic problem.

As a third important advance we should note the increased knowledge in celestial mechanics, which is inspired by space research and made possible by modern computers. Celestial mechanics once lead the break-through of modern physics, but went out of the focus to physicists at the beginning of this century, and many scientists had the feeling that little could be gained by further investigations of the dynamics of the solar system. The last decade, however, has signaled a rebirth of celestial mechanics, which is important for our problem.

2. The state of the solar system at the end of the cosmogonic process

When we try to trace the origin of the solar system, we are discussing processes which occurred a few billion years ago. *A priori* we cannot be sure that there is any possibility of reconstructing what happened long ago. There have been so many events in the past, which have left no trace at all--from the formation of the first living organisms to the performance of perfect crimes. Are there really reasons to believe that we can reconstruct essential features of the cosmogonic process?

The traces which have been left consist of 9 major planets, encircled by at least 31 satellites, plus a great number of asteroids of which more than 1700 are catalogued. To this we should add the comets and the meteors.

The study of these bodies supplies us with data of interest both to the physicist and the chemist. The essential physical data are the masses, the diameters, the moments of inertia, the spin, and the orbital elements of the bodies. So far chemical laboratory data are obtainable only from the earth's surface and from meteors which have fallen down. Furthermore, spectroscopic observations of planetary atmospheres have given valuable chemical information.

What part of this knowledge has reference to the cosmogonic process? The chemical evidence is of course very valuable, but only if we can correct for all the chemical changes during the past few billions of years. In most cases this is difficult. For example, the geological transformations of the earth involve many uncertain factors, and not much is known with certainty about the internal chemical composition of the earth. There are several admirable theories about the internal constitution of other planets, but whether they are correct or not can only be decided when we have visited these places and made the chemical analyses *in situ*. One should therefore be somewhat careful in drawing rash conclusions from chemical data. When famous chemists first create seven moons around the earth and then destroy six of them merely to obtain our Moon as a net result, we should hail them as worthy descendents of the alchemists and rather the demiurges. But we should subject their theories to the tests of celestial mechanics before we accept them.

My prejudice against cosmogonic chemistry may stem from my general ignorance of chemistry. But let us see, in any case, what we can conclude from an analysis of the physical data. We start with a discussion of the axial rotation, the spin, of the celestial bodies.

3. The spin of the celestial bodies

Photometric registrations of asteroids show intensity variations which must be interpreted as due to rotation of a body with nonuniform albedo. Several investigators have measured the periods of axial rotation of 27 asteroids and find no systematic dependence on the magnitudes of the asteroids. In fact, as is shown in Fig. 1, almost all asteroids have periods which deviate by less than 50% from an average of 8 or 9 hours. (It appears that this result is not due to observational selection.)

Regarding the planets, we find that also the giant planets have about the same period. It has always struck students of astronomy that the axial rotations of Jupiter, Saturn, and Uranus are almost equal. The period of Neptune is somewhat longer (15^h), but a correction for the tidal breaking of its retrograde satellite brings it down, at least somewhat. If Lyttleton's suggestion that Pluto was once ejected from the Neptunian system is correct, the correction would be larger. For the earth we should use the period before the capture of the Moon, which according to Gerstenkorn was most likely five or six hours.

Hence we find the very remarkable fact that the axial period is of the <u>same</u> order of magnitude for a number of bodies with <u>very different masses</u>. In fact, when the mass varies by a factor of more than 10^{11}--from less than 10^{19} g (for small asteroids) up to more than 10^{30} g (for Jupiter)--the axial period does not show any systematic variation. We may call this the <u>law of isochronic rotation</u>.

Obviously this law cannot be applied to bodies whose present rotation is regulated by tidal action. Most satellites are probably examples of such bodies as is discussed by Sir Harold Jeffreys in his book "The Earth." Their axial periods are made equal to the orbital periods by the tides produced by their mother planets. Of the planets the axial period of Mercury is 2/3 of the orbital period, which according to Colombo and Shapiro is due to a tidal resonance. Further, Venus exhibits a most remarkable spin-orbit coupling, as recently discovered by Charpenter and Goldreich.

Excepting the bodies which are strongly influenced by tides, the only body with a known rotation far from the order of 10^h is Pluto which rotates in 6 days. Also Mars (period 25^h) shows a rather large deviation.

Concerning the mechanism producing the equality of the axial periods the following conclusions can be drawn.

(i) The equality of the periods cannot be produced by any factor acting today. For example, we cannot expect that the rotation of Jupiter is affected very much by any reasonable forces acting now.

(ii) The equality of the periods cannot have anything to do with the rotational stability of the bodies. The giant planets, for example, are very far from rotational instability today. It is unlikely that one could find a mechanism by which the present isochronism can be connected with rotational instability during the prehistory of bodies as different as a small asteroid and a giant planet.

(iii) Hence the isochronism must be of cosmogonic origin. All the bodies must have been agglomerated by a process which has the characteristic feature that it makes their axial periods about equal, no matter how much mass is acquired. A two-step process for agglomeration, which has this property, has been suggested.

(iv) The braking of the axial rotation of the bodies has not been very significant since their agglomeration. A braking produced by a surrounding uniform viscous medium should lengthen the period of a small body much more than the period of a larger body. The fact that asteroids as small as ten kilometers rotate with the same periods as the largest planets indicates that not even such small bodies have been braked very much since they were formed. In essential respects the solar system seems to be in the same state now as when it was formed. This makes it reasonable that cosmogonically important results can be obtained from detailed analysis of the present state of the solar system.

(v) The isochronism shows further that the asteroids cannot derive from a broken-up planet. If a planet explodes (or is disrupted in some other way) we should expect an equipartition of the rotational energies of the parts. This means that the periods of axial rotation of the smallest asteroids should be much smaller than those of the larger asteroids. This is in conflict with observations.

4. Orbital elements

Concerning the orbital elements, these are subject to secular variations within certain limits. The question whether the solar system is dynamically stable for billions of years has earlier been discussed rather much. I am not sure that there exists yet any rigorous proof of the long-time stability of the system, but it is usually believed that it has a high degree of stability. We are probably justified in assuming that most of the orbits of today are rather close to the orbits in which the cosmogonic process put the celestial bodies.

Exceptions from this general rule are the cases when tidal effects have changed the orbits considerably. The most noteworthy example of this is the Earth-Moon system. It is well known that the tides make the Moon's distance increase, which--extrapolating backwards in time--means that earlier the Moon was much closer to the earth. This is a problem which attracted the attention of Darwin and quite a few others of the old masters of celestial mechanics. Darwin calculated the variations of the Moon's orbit, but for some reason he stopped his calculations just when they became really interesting. He left the problem of the prehistory of the Moon to be solved half a century later by Gerstenkorn, who demonstrated that earlier, when the Moon was closer to the earth, the inclination of its orbital plane was much higher than now. Still earlier the plane was inclined 90° towards the earth's equatorial plane, which means that the Moon passed over the North and South poles, and before that the Moon moved in a retrograde orbit. As the tides make a retrograde orbit shrink, the Moon was still earlier at a larger distance from the earth. From Gerstenkorn's calculations we may conclude that the Moon was originally a planet--perhaps a sister of Mars--which was captured by the earth in a retrograde orbit.

The minimum distance of the Moon was very close to the Roche limit, according to Gerstenkorn. (McDonald and Sorokin have obtained somewhat different results.) The tides which the Moon produced at that time were about 6 km high and may have produced geologically traceable effects. It is of interest to note that an American geologist, Olsen (1966), recently has tried to identify the Gerstenkorn event with a remarkable event 700 million years ago, which usually is interpreted as a world-wide glaciation. Cooper, Richards, and Stacey (1967), on the other hand, suggest that the close approach of the Moon resulted in an internal heating of the Earth, which, according to geological evidence, took place more than 2×10^9 years ago. I am not a geologist so I cannot have any opinion about these, except that they seem to be very interesting suggestions.

We may consider the Neptune-Triton system to be an analogue to the Earth-Moon system, but less developed. Triton moves in a retrograde orbit similar to what the Moon did in the beginning of its captivity.

Whether tidal effects have been important in other cases too, is not quite clear, but probably they have not changed any other orbits drastically. There are also important resonance effects, e.g., in the Jovian and Saturnian satellite systems, which deserve attention in this connection.

5. Celestial mechanics as a deep-freeze

The general conclusion is that--with the mentioned exceptions--the solar system is today in about the same state as it was left by the cosmogonic processes. Not very much has happened during the last few billion years. The celestial mechanics has acted as a very good deep-freeze for the products of our cosmogonic factory.

6. Planetesimal agglomeration

Let us therefore jump back over the rather uninteresting last few billion years to the time when the cosmogonic processes were still active. At that time the situation on the earth was probably rather dull, because it had been raining solid particles continuously for a few hundred million years. It was not a very heavy rain, but it gave a precipitation of an inch or two per year, now and then cheered up by the more dramatic fall of a few giant meteors. The meteors need not necessarily have heated the earth very much. We could depict the earth as moving in a region similar to the present asteroid belt. Only the density of "asteroids" should be several orders of magnitude higher so that the impacts were very frequent.

We are here following the picture of the "planetesimal" theory of the build-up of planets and satellites. This was originally proposed by Moulton, Chamberlain and by Schmidt, and at least in part it is probably correct. The reservation one has to make is connected with the isochronism of planetary rotations.

It has been believed that if a planet like the earth moves in a Kepler orbit it will collect "grains" or "planetesimals" moving in Kepler orbits at approximately the same solar distance. As shown by Dole (1962) this picture is much too simple. When the grains approach the earth they will move in very complicated orbits (see Fig. 2). According to his analysis, which however is confined to circular orbits, grains in 14 different bands, 7 outside and 7 inside the earth's orbit, will hit the earth. Giuli (1968) has calculated the angular momentum which such particles would transfer to the earth. We shall discuss his results in the following.

7. The cosmogonic plasma

In our walk backwards through the ages we have now reached the stage when we must ask the question: where did the "grains," the "planetesimals," come from and how did they acquire the momenta which now define the orbits of the celestial bodies. The answer is that they must have condensed out of a plasma which filled certain regions of our solar system. This means that the general cosmogonic process is supposed to be

$$\begin{tikzcd}
 & \text{Plasma} \arrow[d] & \\
 & \text{Grains} \arrow[d] & \\
 & \text{Embryos} \arrow[r] \arrow[dl] \arrow[d] & \text{Asteroids} \\
\text{Planets} & \text{Satellites} &
\end{tikzcd}$$

The next questions are logically: from where did the plasma come, why was it accumulated in those regions where we now find the celestial bodies, and how was it put into motion? By asking these questions we pass from the field of celestial mechanics into plasma physics and magnetohydrodynamics. We also pass from a field where every problem seems possible to solve--allowing enough computer time--to a field which is much more complicated and less well developed, and consequently more controversial.

As a specific question we ask why so much mass was accumulated in the region of the giant planets and so little in the asteroid region. Also, why is the Jovian satellite system so different from the Saturnian and why has Saturn, and Saturn alone, a ring? Questions of this type must be answered by investigating the dynamics of the plasma from which the grains once condensed.

It is always the dream of a theoretical astrophysicist to start from "initial conditions" and work out in a straight-forward way what must happen according to the laws of physics. The cosmogonic problem is not suitable for such an approach. The "initial conditions" are associated with the formation of stars and this process is not very well understood. Further, we know far too little about the general behavior of cosmic plasmas in order to carry out such an analysis.

Instead our approach must be that of an archeologist who draws his conclusions from combining a number of different findings. We should not look for <u>the</u> cosmogonic theory, "the true one," according to our stanzas, which solves the whole problem at once, but for a number of theories clarifying the great multitude of detailed questions of which the total cosmogonic problem consists.

8. Planetary system versus satellite systems

In the past most cosmogonic theories have aimed primarily at explaining the formation of the planets, whereas the satellite systems have only received secondary interest. The investigators seem to have shut their eyes to the existence of satellites. However, the satellites do exist and are even more numerous than the ordinary planets. We know only one planetary system, but we know three well developed satellite systems--those of Jupiter, Saturn, and Uranus.

These systems are so strikingly similar to the planetary system that any acceptable theory must account for the general formation of small bodies--satellites or planets--around a central body, be the central body a planet or the sun. Conclusions from a general theory can then be confronted with three satellite systems, but only with one planetary system. This fact shows that, from a scientific point of view, we should concentrate our interest on the satellite systems.

There is another, and very important, argument for directing the attention to the satellite systems. The planets conceivably might have been produced from matter ejected from the Sun for example during a collision with another star or a nova outburst. In contrast, it seems highly improbable that the giant planets have produced their satellite systems by ejection of matter. Hence, if we direct our attention to the formation of the satellites, a number of hypotheses which seem plausible for the formation of the planetary system can be ruled out.

Regarding the formation of the planetary system, a theory has great freedom in choosing the initial conditions, because rather little is known about the conditions around the Sun when the planetary system was formed.

But if the planets and the satellites were formed by the same process, this process, when producing planets, must have led to a state which should be the initial state for the satellite formation. Hence, for satellite formation the choice of ad hoc hypotheses is much more limited.

It is possible that in certain respects the state around Jupiter, Saturn or Uranus when their satellite systems were formed was similar to the present conditions in the magnetosphere of the earth. I believe that one can make a series of investigations in the magnetosphere which will spread light on the cosmogonic problem.

The orbital elements of planets and satellites are known with high accuracy. Furthermore, the masses of the planets (except Pluto) are accurately determined, and the masses of the satellites are also known although less accurately. Hence, in order to exclude as many uncertain speculations as possible, it is reasonable to work out a theory of the masses and orbital elements. Most important of the latter is the average distance to the central body (semi-major axis). This means that the first approach to a cosmogonic theory should essentially be a theory of the mass distribution within the solar system.

Our discussion has so far mainly served to spot what processes are essential to the cosmogonic problem. We have found that a number of earlier hypotheses can be excluded. Tidal theories may in principle explain the generation of planets, but certainly not of satellites. The idea of protoplanets much larger than the present ones cannot be reconciled with the isochronic rotation.

9. Plasma processes

So far our results are negative. What are then the positive results? I am not going to give a more detailed description of the processes I believe to have been most important--I have done so elsewhere. I shall confine myself to indicating the general types of the processes. They should produce the following results:

1. Accumulation of the plasma in the regions where the secondary bodies are found. This process is--I believe--rather controversial.

2. Transfer of angular momentum from the central body to the plasma, in such a way that the plasma begins to revolve with approximately the Kepler velocity. It is rather generally agreed nowadays that this transfer is produced by magnetohydrodynamic effects. In other words, it is due to the magnetisation which we must assume the central bodies to possess.

3. In the plasma a formation of grains (or droplets) must take place. These grains should be the raw material for building up asteroids, satellites or planets according to the laws of celestial mechanics, as we have discussed earlier.

Conclusions

I think we can conclude that the cosmogonic problem is now passing from the era of speculation--which is always the first phase of a scientific problem--to the state when a more systematic scientific analysis is possible. One can define rather well a number of problems the solutions of which are necessary before a further advance is possible. Some of these are in the field of celestial mechanics: we want to find the state of the solar system at the moment when the cosmogonic processes ended. We also want to understand the process which gave the celestial bodies the spin they possess.

Among the plasma processes the transfer of angular momentum to a cloud of plasma is reasonably well understood but should be studied in more detail.

In astrophysics the problem how the stars generate their energy could not be solved until nuclear physics was developed so that the fusion processes were understood. Similarly it seems reasonable that a general agreement about the basic principles of the cosmogonic process cannot be reached until plasma physics including magnetohydrodynamics has reached a certain level. The rapid progress in this field gives us reason to be optimistic about the future of cosmogony. On a somewhat longer time-scale much important information will be gained when space research makes it possible to investigate the celestial bodies closer.

It is likely that we shall be able to understand at least the main features of the cosmogonic process. How much of the details one can trace is difficult to say. To many questions our only answer will be ignorabimus. After all none of us had the privilege of watching the process of creation.

ON THE ORIGIN OF THE SOLAR SYSTEM

II. Accretion of Planets

1. Isochronism

Most planets and asteroids which have not been braked by tidal effects spin with about the same period (9 hours ±50 percent). This empirical "law of isochronism" holds for bodies as different as small asteroids and giant planets. In fact, if the planetary mass varies by more than 10^{11}, no systematic change of the period is indicated (Alfvén, 1964).

From a theoretical point of view the isochronism speak definitely against the common view that planets are a result of a direct condensation from a gas cloud. If that were the case the spin of a body should depend upon the size and original rotation of the cloud. It is very unlikely that direct condensation should give the same spin period to a small asteroid and to a giant planet. The isochronism is also adverse to the idea of "protoplanets" much bigger than the present bodies.

Theoretically we can expect isochronism if the condensation takes place in two steps. First the cloud condenses to a number of small grains, and these are later accreted by the gravitational attraction of a growing planetary "embryo." If a grain, initially at rest in relation to the embryo, and at large distance from it, is attracted by its gravitation, the grain will hit the embryo with approximately the "escape velocity"

$$v_e = (2KM/R)^{\frac{1}{2}} = \left(\frac{8\pi}{3} K\right)^{\frac{1}{2}} \theta^{\frac{1}{2}} \cdot R$$

$$= 0.75.10^{-3} \theta^{\frac{1}{2}} R$$

where R is the radius, θ the average density and M the mass of the embryo.

(K is the constant of gravitation.) If a grain reaches the surface of the embryo in the tangential direction, its velocity corresponds to an angular velocity $\omega = v_e/R$ or

$$\omega_e = (8\pi K/3)^{\frac{1}{2}}\theta^{\frac{1}{2}}$$

which is independent of the size of the body but depends on the average density θ. The corresponding period is

$$T_e = \frac{2\pi}{\omega_e} = 0.84.10^3\theta^{-\frac{1}{2}} \text{ sec g}^{\frac{1}{2}} \text{ cm}^{-3/2}$$

$$= 2.34\theta^{-\frac{1}{2}} \text{ hours g}^{\frac{1}{2}} \text{ cm}^{-3/2}$$

Obviously a body does not accrete grains hitting it in such a systematic way. In a realistic case when the grains hit under different angles, the angular velocity ω of the body becomes smaller:

$$\omega = C'\omega_e$$

where C' (<1) is a function of the distribution of the angles of incidence. (C' is related to the constant C defined in reference (Alfvén, 1964) by the relation $C' = 9/10 \cdot C$.) For a homogeneous distribution C' is zero (no spin).

The properties of an accretion of this type have been studied using a simple model. In a plasma cloud rotating with the uniform angular velocity Ω around an axis through the center of the embryo, a condensation of grains takes place. The embryo accretes those grains which hit it. The result is that the embryo will spin with a period

$$T = T_e/C'$$

A numerical calculation gave

$$C' = 0.41$$

or

$$T\sqrt{\theta} = 6.7 \text{ hours} \quad .$$

The value is independent of the size of the body, in agreement with the observational isochronism--but compared to the observational value of about 15 hours $g^{-\frac{1}{2}}\ cm^{-3/2}$ it is too small by more than a factor of 2.

2. Giuli's Theory of Accretion

Another, more realistic model of planetary accretion has been studied by Giuli. Starting from the general "planetesimal" picture of accretion he assumes that the embryo of a planet, e.g., the earth, orbits in a circle around the sun. At the same time there is a uniform distribution of grains which when at large distance from the earth move in Kepler orbits around the sun. When a grain comes in the neighborhood of the embryo it is attracted gravitationally. If it hits the embryo, it is assumed to stick. The mass of the embryo will increase and at the same time the grain transfers angular momentum to the embryo. The ratio between angular momentum and mass determines its spin.

Dole (1962) has demonstrated that in order to hit an embryo moving in a circular orbit around the sun, the grains must be moving within certain "bands," the orbital elements of which he calculates for the case when the grains before approaching the earth move in circular orbits around the sun. Giuli has made similar calculations including also grains moving in eccentric orbits. (Like Dole, he restricts his calculations to the case when the particles move in the orbital plane of the embryo.) Further, he has calculated the spin which a growing planet attains when it accumulates mass in this way.

He finds, that a planet capturing exclusively grains moving in circular orbits, will acquire a retrograde rotation. However, if accretion takes place also from eccentric orbits, the rotation will be prograde (assuming equal grain density in the different orbits). This effect is essentially due to a sort of resonance effect which makes the accretion from certain eccentric orbits very efficient. Such orbits are ellipses with $a > 1$ (a = semi-major axis, with earth's orbital radius taken as unit) which at perihelion graze the earth's orbit in such a way that the grain moves with almost the same velocity as the earth. There is also a class of orbits with $a < 1$, the aphelion of which gives a similar effect. In both cases a sort of focusing occurs in such a way that the embryo receives a strong prograde spin.

Giuli treats his problem in a coordinate system xy which has its origin at the center of the earth. The sun is very far in the -x direction. The coordinate system rotates with the period of one year. Taking the sun-earth distance as length unit and one year as time unit, the equations of motion close to the earth can be written approximately:

$$\ddot{x} = -\frac{Mx}{r^3} + X$$

$$\ddot{y} = -\frac{My}{r^3} + Y$$

where M is the mass ratio earth sun and

$$X = 2\dot{y} + 3x$$

$$Y = -2\dot{x}$$

The rotation of the coordinate system introduces the Coriolis force ($2\dot{y}$, $2\dot{x}$) and the inhomogeneity of the solar gravitation the force ($3x$, 0). These forces together disturb the ordinary Kepler motion around the planet. The capture is most efficient for particles moving through space with approximately the same speed as the earth. These particles will hit the earth at approximately the escape velocity v_e. We can discuss their orbits under the combined gravitation of the earth and the sun in the following qualitative way.

Let us reverse time and shoot out particles from the earth. In case a particle is shot out from the 6^h point of the earth ($x = 0$, $y = r$) in the eastward direction with slightly less than the escape velocity, it will move in an ellipse out in the $-y$ direction towards its aphelion A. (See Fig. 3.) The Coriolis force $2\dot{y}$ and the solar gravitation gradient $3x$ will act in opposite directions so as to minimize the net disturbance. On the other hand, on a particle shot out in the westward direction from the 6^h point the two forces will add in such a way as to deflect it from the ellipse far out from the earth's gravitational field, where it will continue with a very low velocity.

Reversing the direction of motion we hence find that particles from outside can penetrate into the earth's field in such a way that they hit the 6^h point of the earth's equator from the west direction but not from the east direction (Fig. 4). Hence the particles form a sort of a jet which gives a prograde spin.

Similarly, particles moving inside the earth's orbit can hit the 18^h point only from the west direction and they also give a prograde momentum.

Thus we have an efficient capture mechanism for two "jets" both giving prograde rotations. They derive from particles moving in the solar field with about a = 1.04 and a = 0.96 and an eccentricity of 0.03. Most other particles hit in such a way that in average they give a retrograde momentum.

Applied to the earth the net effect of the process is according to Giuli a prograde spin with a period of 15 hours--a value which is of the correct order of magnitude, but larger by a factor of two or three than the earth's period before the capture of the Moon (5 or 6 hours). Giuli finds that a body with the radius 0.1 $R_{\oplus}$ and the same density will get the same period. It is likely (although not definitely proved mathematically) that the period is proportional to $\theta^{-\frac{1}{2}}$ (θ = density of the body, assumed to be homogeneous). The value of $T\sqrt{\theta}$ which is obtained in this way is

$$T\sqrt{\theta} = 35 \text{ hours } g^{\frac{1}{2}} \text{ cm}^{-3/2}$$

This value is larger by a factor of two than the average for all planets--including asteroids--which are not affected by tidal braking.

Giuli's calculations are based on the simplest possible planetesimal model, viz that an embryo grows by accretion of those grains which hit it. Hence he has neglected collisions between the grains. It is highly satisfactory that this simple model gives the correct order of magnitude for the spin. It is reasonable to interpret this agreement as a strong support for the theory of planetary accretion.

Giuli's model is two-dimensional. It seems unlikely that a three-dimensional model will change the results in a more drastic way but a change in the numerical value by a factor of--say--two, is very well possible.

3. Accretion and Isochronism

The agreement between Giuli's theory and the observed spin period suggests that we may begin to understand essential features of the accretion of the celestial bodies in our solar system . (It should however be observed that the theory is two-dimensional and that a proof of the dependence of the period on the average density is still lacking.)

The general mechanism of accretion may then be described in the following way. By a process which we shall not discuss here space around the central body (sun or mother planet) is filled with small grains which have condensed out of a plasma. The grains move in Kepler orbits, in general with a certain eccentricity. In reality their orbital planes do not coincide, but as Giuli's theory is two-dimensional, we take no account here of the orbit inclinations.

The grains increase in size and in number, and begin to interact with each other. Collisions between the grains are inelastic, and the general result is a build-up of larger grains. As soon as the grains have become large enough to have appreciable gravitational effects on the surrounding, Giuli's mechanism will be efficient with the result that the spin of the grains attains the isochronic value.

We can visualize that in this way an embryo can be formed with, for example, a diameter of some hundred meters, feeding from grains of the size of centimeters or less. Larger bodies, for example bodies of the size of small asteroids, may also increase their mass by collecting such small grains. However, the increase in mass is mainly due to the collection of larger bodies which already have been formed in the region where they move. In a similar way we can think of large asteroids--like Ceres--as accreted mainly from minor asteroids. The process may proceed in such a way that our present planets have accreted mainly from bodies of the size of, for example, Ceres.

The outlined process is a successive building-up of larger bodies from smaller ones. As the basic process is independent of mass we can understand why the spin period remains the same when the mass varies by a factor of 10^{11} from the smallest asteroids to the giant planets.

ON THE ORIGIN OF THE SOLAR SYSTEM

III. Partial Corotation of a Magnetized Plasma

1. The Ferraro isorotation and partial corotation

If a magnetized celestial body rotates with the angular velocity Ω, it has a tendency to make a plasma in its surrounding share its rotation. Hydromagnetic effects work towards the establishment of isorotation, which means that all parts of the plasma rotate around the axis with an angular velocity ω which equals Ω. The problem has been studied by Ferraro and later by Alfvén and others (cf. Alfvén and Fälthammar 1963, p. 109). The most detailed study is due to Lüst and Schlüter (1955).

The transfer of angular momentum is of basic importance to the understanding of the formation of the solar system.

In the mentioned papers it was assumed that not only the central body but also the surrounding medium has infinite conductivity, which means that the magnetic lines of force are "frozen-in." However, recent studies of the conditions in the terrestrial magnetosphere indicate the presence of electric fields parallel to the magnetic field (Persson 1963, 1966). As such electric fields may "cut" the magnetic lines of force, this implies that the magnetic lines of force are not necessarily frozen-in (see Alfvén-Fälthammar 1963, p. 190). For example even if the magnetic field is a perfect dipole field the angular velocity ω of a plasma cloud may differ very much from Ω under the condition that there are electric fields parallel to the magnetic field in a region intermediate between the central body and the plasma cloud. This requires that in the intermediate region the density is so low that the mean free path is long compared to the linear dimensions (e.g. the distance to the dipole).

It seems plausible that very often the transfer of angular momentum is stopped long before $\omega = \Omega$, so that only a state of partial corotation is reached.

The purpose of the present paper is to study this state and especially the condensation of grains from it, a process which is of importance to the cosmogonic problem. The results are applied to the cosmogony of the Saturnian rings and the asteroid belt.

2. Plasma in a magnetic dipole field under the action of gravitation

Suppose that an electrically conducting rotating sphere with mass M has a magnetic dipole field the axis of which is parallel or antiparallel to the axis of rotation. Let us introduce a spherical coordinate system (r, λ, φ) (see Fig. 5). We shall investigate a stationary state with cylindrical symmetry (variables independent of t and of φ). Consider a small (ring shaped) plasma cloud at (r, λ), the elements of which rotate around the axis with the velocity

$$v_\varphi = \omega\, r \cos\lambda \tag{1}$$

In this cloud a particle with mass = m is acted upon by the gravitation

$$mf_g = \frac{KMm}{r^2} \tag{2}$$

and by the centrifugal force

$$mf_c = \frac{m\, v_\varphi^2}{r \cos\lambda} \tag{3}$$

The gravitation acts antiparallel to the vector radius which makes the angle α with the magnetic field. We have

$$\sin \alpha = \frac{\cos \lambda}{\phi} \; ; \; \cos \alpha = \frac{2 \sin \lambda}{\phi} \tag{4}$$

with

$$\phi = (1 + 3 \sin^2 \lambda)^{1/2} \tag{5}$$

(Cf. Alfvén and Fälthammar 1963, p. 4.)

The centrifugal force makes the angle $\lambda - \alpha$ with the magnetic field. We find from (4)

$$\cos (\lambda - \alpha) = \frac{3}{2} \cos \lambda \cos \alpha \tag{6}$$

If the medium between the plasma cloud and the sphere has a high electric conductivity, the plasma cloud must corotate with the sphere. This implies--among other things--that the mean free path must be small compared to the linear dimensions. However, if the medium has a very low density so that the mean free path is long, there may be electric fields parallel to the magnetic field (H. Persson 1963, 1966). Then even in a stationary state the rotation ω of the plasma cloud may differ from the rotation Ω of the central sphere. We shall investigate this case, assuming that the region between the central body and the plasma cloud is a "low density plasma."

If the temperature is zero a particle with charge e and mass m is acted upon by a force which has the component mf'' parallel to the magnetic field:

$$mf'' = - mf_g \cos \alpha + mf_c \cos (\lambda - \alpha) + eE'' \tag{7}$$

where E'' is the electric field parallel to the magnetic field B. A fraction γ of the atoms of the plasma are ionized. Adding the electron, ion and atom components we obtain the total force F'' action on a volume element containing

$(1 - \gamma)n$ atoms (mass m_a), γ electrons and γ ions. We find

$$\frac{1}{n} F'' = m_a [- f_g \cos \alpha + f_c \cos (\lambda - \alpha)] \tag{8}$$

In a stationary state F'' must be zero.

Because of the symmetry no force acts in the φ direction. This means that the drift perpendicular to B in the meridian plane is zero. The force perpendicular to B in the meridian plane is

$$mf^{\perp} = mf_g \sin \alpha + mf_c \sin (\lambda - \alpha) + eE^{\perp} \tag{9}$$

The first two terms give drifts in opposite directions to ions and electrons. In this way a drift current i is produced which gives a force

$$f^{\perp} = i \cdot B \tag{10}$$

withe the magnetic field, preventing the plasma from moving perpendicular to B in the meridian plane. We assume that the current i in (10) is so small that it does not modify the dipole field considerably. In the cases of interest to us, this is equivalent to the requirement that the gravitational energy of the plasma should be negligible compared to the magnetic energy.

The electric field $E^{\perp}$ in (9) gives an additional drift so that the total drift produced by $f^{\perp}$ equals the rotation with the velocity (1).

3. Stationary motion of magnetic plasma

We have treated an element of a medium density plasma situated at (r, λ, φ) in a magnetic dipole field from a rotating central body, from which it is separated by a low density plasma. We have assumed that the temperature of the plasma is low. Further we have assumed that the mass is so small that the dipole field is not seriously disturbed. A stationary rotation of the plasma requires $F'' = 0$, which according to (9) means

$$f_g \cos \alpha = f_c \cos (\lambda - \alpha) \tag{11}$$

With the help of (1), (2), (3) and (4) we find:

$$v_\varphi^{\ 2} = \frac{2}{3} \frac{KM}{r} \tag{12}$$

As a comparison a circular Kepler motion is characterized by

$$v_K^{\ 2} = \frac{KM}{r} \tag{13}$$

Hence in a magnetic dipole field a plasma element has a stationary motion if it has a <u>partial corotation, the kinetic energy of which is 2/3 of the kinetic energy of a circular Kepler motion</u>.

This factor derives from the geometry of a dipole field and enters because the centrifugal force makes a smaller angle with a field line than the gravitation. The plasma element is supported against gravitation in part by the centrifugal force, but in part by the current i which according to (10) gives a force with the magnetic field.

The following table compares the energy and angular momentum of a circular Kepler motion and a circular motion of a magnetized plasma.

	Circular Kepler Motion	Partial corotation of magnetized plasma
Gravitational energy	$-\frac{KM}{r}$	$-\frac{KM}{r}$
Kinetic energy	$\frac{1}{2}\frac{KM}{r}$	$\frac{1}{3}\frac{KM}{r}$
Total energy	$-\frac{1}{2}\frac{KM}{r}$	$-\frac{2}{3}\frac{KM}{r}$
Angular momentum $c = r \cdot v$	$\sqrt{KM\, r}$	$\sqrt{\frac{2}{3} KM\, r}$

4. Effect of finite temperature

If the plasma temperature differs from zero, diamagnetic repulsion from the dipole gives an outward force which has a component which is added to the centrifugal force. This makes the factor in (12) smaller than 2/3. It can be shown that this effect is of importance if $A = \gamma k(T_e + T_i)$ (where γ is the degree of ionization, k Boltzman's constant, and T_e and T_i the electron and ion temperatures) is comparable to the kinetic energy $W_k = \frac{1}{2} m_a v_\varphi^2$ (where m_a is the mass of an atom in the plasma). For a possible application to the close environment of Saturn we may put $m_a = 10\ m_H = 1.7 \cdot 10^{-23}$g, $v_\varphi = 2 \cdot 10^6$ cm/sec (= orbital velocity of Mimas), $\gamma = 10\%$. We find that $A/W_k = 1\%$, if $T_e = T_i = 15000°$K. This indicates that the temperature correction is probably not very important in the case we have considered.

5. Condensation of the plasma

If the plasma recombines so that the current i vanishes, the element of matter changes its motion from the type we have investigated, and under certain conditions its motion will be a Kepler ellipse.

Let us suppose that in the plasma a condensation takes place so that small "grains" are produced. The condensation may lead to small solid bodies or to droplets or--according to Opik--in some cases to "snowflakes." We shall not discuss the process of condensation more in details, but refer to its product as "grains." If these are very small the electric charge they may acquire in the plasma may make their motion influenced by the magnetic field. We shall confine the discussion to the simple case when the grains are so large that they neither are influenced by electromagnetic forces, nor by friction with the plasma. Furthermore, the condensation is supposed to be instantaneous so that the initial velocity of a grain equals the velocity of the plasma element from which it is born.

Under these assumptions a grain produced at the point $(r_0, \lambda_0, \varphi_0)$ will move in an ellipse with the eccentricity

$$e = \frac{1}{3}$$

Its aphelion is situated at $(r_0, \lambda_0, \varphi_0)$ and its perihelion at $(r_1, \lambda_1, \varphi_1)$ with

$$r_1 = \frac{1}{2} r_0$$

$$\lambda_1 = - \lambda_0$$

$$\varphi_1 = \varphi_0 + \pi$$

The ellipse intersects the equatorial plane $\lambda = 0$ at the nodal points $(r_n, 0, \varphi_0 + \frac{\pi}{2})$ and $(r_n\ 0, \varphi_0 - \frac{\pi}{2})$ with

$$r_n = \frac{2}{3} r_0$$

When the grain reaches r_n its angular velocity equals the angular velocity of a body moving in a Kepler circle in the orbital plane of the grain.

Suppose that grains are produced in a ring element (r_0, λ_0) of plasma. All of them cross the equatorial plane at the circle $r_n = 2/3\ r_0$. Suppose that there is a small body ("embryo") moving in a circular Kepler orbit in the equatorial plane with radius r_n. It will be hit by the grains, and we assume that all grains hitting it are absorbed by it. Each grain has the same angular momentum per mass as the embryo. However, the angular momentum vector of the embryo is parallel to the dipole axis whereas the angular momentum vector of the grain makes an angle λ_0 with the axis. In case λ_0 is so small that we can put $\cos \lambda_0 = 1$ the embryo will grow in size but not change its orbit. If $\cos \lambda_0 < 1$ the embryo will spiral inwards when growing.

Seen from the coordinate system of the moving embryo the grains will reach it with a velocity vector in the meridional plane. Its component parallel to the axis is $(2/3 \frac{KM}{r_0})^{1/2} \sin \lambda_0$ and the velocity component in the equatorial plane $(1/12 \frac{KM}{r_0})^{1/2}$. If the collision is perfectly inelastic the corresponding energy is transferred into heat.

6. Conclusions

Summarizing our results we have found that a plasma cloud in the dipole field of a rotating central body need not necessarily attain the same angular velocity as the central body. If in the region between the plasma cloud and the central body the density is so low that the parallel electric field may differ from zero a stationary state is possible characterized by a partial corotation according to the table in § 3. If at a central distance r_0 "grains" condense out of such a plasma, they will move in ellipses with a semi-major axis $2/3\ r_0$ and an eccentricity $e = 1/3$. Mutual collisions between a population of such grains will finally make the condensed matter move in a circle in the equatorial plane with the radius $2/3\ r_0$.

In the more general case when condensation takes place in an extended region one should expect that the mass of each grain which has condensed shall ultimately be moving in a circle at a distance of 2/3 times the distance where the condensation has taken place. This may occur under certain conditions, but is not necessarily true, because collisions between the grains is no more restricted to the equatorial plane. There will be competitive processes through which grains agglomerate to larger bodies moving in eccentric orbits. However, the semi-major axes of these orbits are 2/3 the weighted mean of the radius vector to the place of condensation.

7. Application to the Saturnian ring system

The structure of the Saturnian ring system can be understood as a result of a condensation from a plasma with partial corotation.

The ring system consists of an outer ring, the A-ring with medium intensity, separated from the very bright B-ring by a dark space, called Cassini's division. Inside the B-ring there is a ring with very weak intensity, the C-ring.

If the grains now forming the different rings have condensed from a partially corotating plasma the regions where the condensation took place should be 3/2 the present distance from the center of Saturn. Hence if we magnify the ring system by a factor 3/2 we should find the position of the plasma from which it once condensed. Such a magnification brings the Cassini's division to coincide with the present orbit of Mimas. Furthermore the limit between the B- and C-rings coincides with the outer edge of the A-ring (see Fig. 6).

The interpretation is the following. Plasma in the vicinity of Saturn was put into partial corotation. Grains condensing from this plasma moved in ellipses with $e = 1/3$ and angular momenta corresponding to circular Kepler orbits at central distances of 2/3 times the distances to the places of condensation. Outside the Roche limit the grains agglomerated to satellites. Similar agglomeration could not take place inside the Roche limit where colliding grains cannot coalesce into larger bodies. Instead the result of the collisions was that the orbits of the grains were changed into circles in the equatorial plane, situated at 2/3 of the central distance to the place of condensation.

The outer border of the A-ring can be identified with the Roche limit. The grains forming the A-ring originate from the region outside the orbit of Mimas.

The region where Mimas moves has been swept, because the plasma has condensed directly on Mimas or perhaps rather on the "embryo" which later formed Mimas. Hence very few grains derive from this region. This explains the present dark spacing called Cassini's division.

From the region inside the orbit of Mimas the grains fell down to form the B-ring. This is brighter than the A-ring because the grains forming the A-ring had to pass the orbit of Mimas. and this satellite captured part of them or perturbed their orbits.

The grains of the B-ring originate from the plasma region inside Mimas' orbit, but outside the Roche limit. However, inside the Roche limit there are a great number of grains which "sweep" the region in the same way as Mimas swept a region near its orbit. The condensation from this region will hence result in a much fainter ring than the condensation from the region outside the Roche limit. This explains the faintness of the C-ring compared to the B-ring.

Hence one can say that Cassini's division is the "cosmogonic shadow" of Mimas and the limit between the B- and C-rings marks the beginning of a similar "shadow" of the A-ring.

A more detailed analysis of the ring system is found elsewhere (Origin of the Solar System, p. 79).

The usual interpretation of the structure of the rings as due to resonance effects is not convincing (loc. cit.). There are no gaps in the ring where resonance effects are expected, and for example Cassini's division is definitely outside the calculated resonance points. The mass ratio of Mimas-Saturn is only 10^{-7} and of Enceladus-Saturn 10^{-6}. The satellites are probably too small to produce any visible resonance effects in the ring system.

8. Application to the asteroid belt

The asteroid belt can also be interpreted as a result of a condensation from a partially corotating plasma. There are certain similarities with the Saturnian rings, but the structure differs in the following respects:

1. In the asteroid distribution (see Fig. 7) there are very pronounced gaps resulting from resonances with Jupiter's orbital period. The mass ratio Jupiter-Sun is 10^{-3}, whereas the ratio Mimas-Saturn is only 10^{-7}. However, resonance effects can explain neither the upper nor the lower limit of the asteroid belt.

2. The reason why the grains forming the Saturn rings have not agglomerated to larger bodies is that they are moving inside the Roche limit. In the asteroid belt the bodies have not agglomerated to planets because the density is too low. As a study of the rotation of the asteroids has shown (Alfvén 1964), these bodies cannot derive from a "broken up planet," but must be identified as a "half product" of the process of planet formation.

The outward border of the main groups of asteroids is situated at a solar distance of 2/3 the distance of Jupiter. Grains condensing outside Jupiter's orbit move in ellipses with e = 1/3 and when they repeatedly cross Jupiter's orbit there is a high chance that either they are captured by Jupiter (or the embryo forming Jupiter) or their orbits are perturbed so that they will not ultimately be found at 2/3 of their place of origin. Hence there are very few asteroids outside 2/3 of Jupiter's orbit. This means that there is no real correspondence to the A-ring of the Saturnian system. Mimas with a mass of only 10^{-7} of the Saturnian mass, has reduced the intensity of the A-ring (compared to the B-ring), but only to a certain extent. Jupiter, with a mass of 10^{-3} of the solar mass, is able to reduce the intensity to close to zero.

Hence the main group of asteroids starts at 2/3 of Jupiter's orbital distance. Rather close below this limit a strong resonance effect takes place. The Kepler orbit with a period which is exactly half the period of Jupiter, is found a small distance below the limit (because $(1/2)^{2/3} = 0.63$ is close to $2/3 = 0.67$). The resonance gap prevents the asteroid population from reaching its full value until at some distance below the limit.

The inner border of the main asteroid group is situated at 2/3 of the distance to the outer border (or rather the distance where the asteroid population reaches its full value). Hence it is an analogy to the border between the B-ring and the C-ring. The asteroids themselves have "swept" the region where they move so that there is no plasma which can condense to grains. In other words the inside limitation of the asteroids group is produced by their "own cosmogonic shadow."

A more detailed theory of the asteroid belt has been given elsewhere (Origin of the Solar System, p. 100).

9. Application to the terrestrial magnetosphere

It is of interest to investigate whether in some parts of the magnetosphere the present conditions are such as to cause a partial corotation. A cloud of plasma, either injected during a magnetic storm or artificially injected, may receive angular momentum from the rotating earth to such an extent that the state of partial corotation is reached.

ON THE ORIGIN OF THE SOLAR SYSTEM

IV. On the Structure of the Saturnian Rings

ABSTRACT

The structure of the Saturnian rings is usually attributed to resonance effects produced by the innermost satellites. It is shown that this theory is inadequate. It seems unlikely that any force acting today can cause the observed structure. Arguments are given for the view that the ring structure is of cosmogonic origin and has been preserved from the time when the rings and the satellites were formed.

The cosmogonic theory of the Saturnian rings is discussed. Both Mimas and the newly discovered Janus seems to have affected the ring structure.

The theory leads to the prediction of a new undiscovered satellite moving between Janus and Mimas.

1. Introduction

The Saturnian ring system consists of three rings: The outermost is called the A-ring and is separated by a drak region called Cassini's division from the B-ring, which is brighter than the A-ring. Inside the B-ring there is the very faint C-ring.

The photometric curve given by Dollfus (Fig. 8) shows that near the outer edge of the A-ring there is a series of light maxima and minima. A double minimum exists near the inner edge of the B-ring. In the middle of the B-ring two minima are visible.

2. The resonance theory of the ring structure

It is usually believed that the structure of the ring system is produced by resonance effects with the satellites. Different investigators have claimed that Cassini's division is due to a resonance with Mimas in the way that the particles in the dark region should be removed because their period is exactly 1/2 of the period of Mimas. The resonance corresponding to 1/3 of the period of Enceladus also falls close to Cassini's division. In a similar way the sharp change in intensity between the B-ring and the C-ring should be connected with the 1/3 resonance with the period of Mimas. A list of claimed resonances has been given by A.F.O'd. Alexander (1953, 1962).

Fig. 8 shows a plot of all resonances with denominators ≤ 10. The resonances with denominators ≤ 5 are marked with thick lines. A number of resonance points of Mimas and Thetys are similar because the period of Mimas is almost exactly half the period of Thetys. The same is the case for the pair Enceladus-Dione. It should be remembered that the periods of Mimas, Enceladus, Thetys and Dione are approximately proportional to 2:3:4:6.

A comparison between the calculated resonance points and the observed pattern of the ring system does not show any obvious connection. The 1/2 resonance of Mimas falls definitely to the left of Cassini's division. Half the period of Mimas differs by 1.2% from the period of the outermost particles of the B-ring and by 4% from that of the innermost particles of the A-ring. The difference between the 1/3 resonance with Enceladus and Cassini's division is still larger. In fact, the figure shows that there is not a single resonance point falling in the gap of Cassini's division. Nor is there any obvious connection between other markings--bright or dark--and the resonance points.

This constitutes a striking difference with the asteroid ring, where there are very pronounced gaps corresponding to integer fractions of Jupiter's period. For example, near the resonances 1/2 and 2/5 of Jupiter's period there is a complete absence of asteroids (see Fig. 9). As Cassini's division has been attributed to resonances which should differ by a few percent, it is of interest to see whether a similar asymmetry exists for the asteroids. With reference to the resonance point the asymmetry of the gaps--if any--is only a fraction of one percent. The half-width is about 1.5%. Hence with the same relative breadth the resonance gaps of 1/2 Mimas' and 1/3 Enceladus' periods would be altogether within the B-ring, and outside Cassini's division. Further there is not the slightest trace of a resonance gap in the B-ring corresponding to either 2/5 of Mimas' period or to 1/3 of Enceladus' period. Hence from an observational point of view there is no real similarity between the asteroid gaps on one side and dark regions of the Saturnian rings on the other. In fact Fig. 8 indicates that if anything is characteristic for Cassini's division it is that not a single resonance point falls in that region.

From a theoretical point of view the systems differ in certain respects. The asteroids have usually rather eccentric orbits whereas the grains in the Saturnian rings move in almost perfect circles. As far as the resonance theories are developed there is no indication that this should produce a systematic displacement of the resonances in the case of the Saturnian rings (which would be the only possibility to describe Cassini's division as a resonance effect).

The most important difference is likely to be the relative strength of the perturbing force. The mass Jupiter is about 10^{-3} of the solar mass, whereas the masses of Mimas and Enceladus are of the order 10^{-7} of the Saturnian mass. As by definition the ratio of the distances from the perturbed bodies to the central bodies and to the perturbing bodies is the same in the two cases, the relative magnitude of the perturbing force is about 10^{-4} times less in the Saturnian rings than in the asteroid ring.

Hence it seems legitimate to doubt whether Mimas and Enceladus are large enough to produce any phenomenon similar to the asteroid gaps. None of the existing theories have demonstrated quantitatively that the Saturnian satellites are large enough to produce any visible resonance gaps.

Further it should be noted that the resonance theories have so far not been able to give an acceptable explanation why the B-ring is somewhat brighter than the A-ring.

Concerning the sharp limit between the B-ring and the C-ring it has been claimed that the 1/3 resonance of Mimas should be responsible for the very large positive derivative of the light curve. However, the 1/3 resonance of Enceladus is situated somewhat inside Cassini's division in a region where the derivative of the light curve is slightly negative. There is no obvious reason why the same resonance with the different satellites should produce so different results.

Our conclusion is that the resonance theories have not succeeded in explaining the main characteristics of the Saturnian rings. Furthermore, it is difficult to imagine that any other force acting at present times could produce the observed structure.

3. Recent or ancient production of the ring structure?

The difficulty in explaining neither the gross structure nor the fine markings as results of forces acting today makes it important to ask whether the structure may derive from the cosmogonic process by which the ring system once was formed. Certainly this approach causes some hesitation because it implies that during the few billion years which have elapsed since the formation of the solar system even the details of the structure should have remained essentially unchanged. This requires that the ring system has an enormous stability. The perturbation theory in celestial mechanics does not allow us to draw any definite conclusions about the behaviour of a satellite system during so long times.

The problem we discuss is somewhat similar to the problem about the isorotation of the planets and asteroids (Alfvén, 1964). Practically all celestial bodies which are known to rotate have about the same period of rotation (unless the spin has been changed by tidal effects) and this cannot be a result of forces acting today. The conclusion is that the isorotation must derive from cosmogonic processes and that--when tidal effects are unimportant--the spin has not changed very much during the time which has elapsed since the formation of the solar system. To ascribe the structure of the Saturnian system to cosmogonic processes means that we admit that the orbital momenta of its constituents have been preserved in a similar way.

4. Cosmogonic theory of the Saturnian rings

The cosmogony of the Saturnian ring system is a special case of the general cosmogonic process which under certain conditions produces secondary bodies around rotating massive magnetized bodies. The reason why Saturn, and Saturn alone, has a ring system has been discussed elsewhere (Alfvén, 1954, 1962). Also the structure of the rings has been analyzed earlier (Alfvén 1942, 1954). However, recent results from the study of the terrestrial magnetosphere seem to be applicable to the cosmogony of the Saturnian rings. Moreover, new observations of the Saturnian system are relevant to the problem.

As has been pointed out recently (Alfvén 1967) the state around a planet when its satellite system was formed was in some respects probably similar to the present state of the terrestrial magnetosphere. It seems likely that in order to produce satellites a planet must be magnetized, and hence surrounded by a magnetosphere. At cosmogonic times the Saturnian magnetosphere was probably not so disturbed by solar activity as the present terrestrial magnetosphere, because it is doubtful whether at that time the sun was very active. Dessler (1966) has pointed out that the solar emission of high speed plasma requires rather special conditions which are satisfied today, but not necessarily during other periods of the life history of the sun. Furthermore, not even at present times, is the solar activity likely to produce very much disturbance as far out as Saturn.

When the satellite systems were formed the density around the central body must have been considerably higher than in the present terrestrial magnetosphere. If we smear out the mass of the Saturnian satellites in a sphere with a radius equal to the orbital radius of the satellite orbits we obtain an average density of the order 10^{-8} g/cm^3. In the theory of Laplace and its modern versions (von Weizsäcker, Kuiper, Berlage) the gas cloud out of which the satellites were formed must have had this density (or perhaps a higher density if only part of the cloud condensed). Contrary to this the magnetohydrodynamic approach, which we are following, envisages a plasma density which on the average was several orders of magnitude smaller. This is a consequence of the assumption that the raw material of the satellites was a neutral gas falling in--continuously or in jets--from a large distance towards the central body. When it reached the "critical velocity" the gas became ionized and formed a plasma in the magnetosphere of the central body. This plasma was brought into partial corotation with the central body, after which it rapidly condensed to small "grains." Because the injection of neutral gas went on during a time which was very much longer than the time it took for the plasma to condense into grains only a small fraction (10^{-6} or perhaps 10^{-9}) of the present mass of the satellites need have been suspended as a magnetized plasma in the surrounding of the central body. On the other hand it is possible that at a certain period all the present mass was in forms of grains ("satellitesimals") moving in Kepler orbits.

Hence the density in the magnetosphere of a satellite-forming planet was probably comparable to the present density of the outer solar corona (10^5 particles cm^{-3} or less). We should envisage that the magnetic field had the same dominating influence on the structure as in the present solar corona and that consequently there were very large local density variations. This means that the average density was some orders of magnitude higher than in the outer parts of the present terrestrial magnetosphere. However, the motion of the plasma was essentially regulated by the magnetic field.

A survey over possible densities and magnetic fields has been given elsewhere (Alfvén 1954).

5. Partially corotating plasma around Saturn

Under certain conditions, which have been specified elsewhere (Alfvén 1967) a plasma in the magnetosphere of a rotating planet will be in the state of "partial corotation." A characteristic of this state is that if condensation of the plasma takes place, the resulting "grains" will have the same orbital momenta as grains moving in circular orbits at central distances equal to 2/3 of the distance where the condensation took place. By inelastic collisions with other grains condensing at the same central distance their orbits may be changed in such a way that we at present times find them in circular orbits at 2/3 of the place of condensation.

We know too little about the conditions in a planetary magnetosphere at cosmogonic times to be able to conclude that the requirements for partial corotation were satisfied. However, from our general lines of approach it is possible, perhaps we may say probable, that partial corotation took place. It is therefore worth while to investigate whether we can find features in the present structure of the solar system which can be interpreted as results of condensation from a partially corotating plasma.

If along this line of approach we want to find the place of origin of present bodies, we should enlarge the present orbits--if they are circular--by a factor 3/2. If we apply this to the Saturnian ring system we find that Cassini's division comes into the region where Mimas moves, and the border between the B-ring and the C-ring coincides with the outer edge of the A-ring. This may be interpreted in the following way.

6. Cosmogonic "shadow" effects

In the region where Mimas moves the rotating plasma will condense on Mimas (or perhaps on the dispersed matter which is in the process of coalescing into the present Mimas). Hence in this region there will be little plasma left to form grains which later will be found at 2/3 of the central distance of Mimas. The plasma outside the orbit of Mimas condenses to grains and when they have fallen to 2/3 of their initial distance they form the present A-ring. However, before they reach this position they have to pass Mimas orbit, and part of them will be captured or perturbed. Hence the density of the A-ring is somewhat reduced. The grains condensing from plasma inside Mimas' orbit fall down to 2/3 of their initial position without passing Mimas' orbit and form the B-ring, the brightness of which is not reduced in the same way.

Hence we may interpret Cassini's division as what we may call the "cosmogonic shadow" of Mimas and attribute the fact that the A-ring is less bright than the B-ring to a partial "shadowing" by Mimas.

As has been stated above the cosmogonic process which we are considering does not envisage that all the matter which at present constitutes the satellites and the rings was at the same time in the state of a plasma in the environment of Saturn. Instead there was a continuous injection of gas--or an injection as a series of jets--going on during a very long time (perhaps 10^8 or 10^9 years). The gas became ionized, brought into a state of partial corotation, and condensed to grains, but these processes were relatively very rapid. This means that at a certain moment only a very small fraction of the total injected gas was in the state of a plasma. Hence the process was producing grains more or less continuously during a very long time.

Outside the Roche limit the grains agglomerated into satellites. Inside the Roche limit the grains did not agglomerate because the disruptive effect due to Saturn's tidal action was larger than the mutual gravitational attraction between the grains. Hence if initially the same average density of matter was injected both outside and inside the Roche limit, the matter inside the limit remained in a dispersed form whereas outside the limit it agglomerated to larger bodies. This means that the total surface of the grains inside the limit may be many orders of magnitude larger than the total surface of the larger bodies, even if in average the mass density is of the same order. As the reflected sunlight is proportional to the total surface, the mass inside the Roche limit is more easily observed than the mass outside the limit.

The absorbtion of plasma on solid bodies is also proportional to the surface of the bodies. Hence we should expect that the plasma which is injected in the region inside the Roche limit will rapidly be absorbed by the grains. In the same way Mimas produces Cassini's division as its "cosmogonic shadow" at 2/3 of its central distance.

Fig. 10 shows in the upper left corner the light curve with the ordinate reversed and the abscissa reduced by a factor 2/3. The expected cosmogonic shadow should be proportional to the total surface of the matter, which means that it should be proportional to the luminosity. The figure shows that the drop in intensity from the B-ring to the C-ring occurs almost exactly where we expect the cosmogonic shadow to appear. In fact Dollfus' value for the outer limit of the A-ring is 18".90 and for the border between the B-ring and C-ring 12".60. The ratio between these values happens to be exactly 1.500 = 3/2. The same ratio calculated from older observations is somewhat higher, up to about 1.55.

When in this way partially corotating plasma is absorbed directly on the grains of the rings, the average angular momentum of the rings will decrease. If we take account of this effect the fall down ratio 3/2 = 1.50 should increase somewhat. According to more detailed calculations a value of the fall down ratio depends on the density distribution of the original plasma. For the density distribution in the Saturnian system a value of about 1.55 is reasonable. An increase in the fall down ratio may also be due to the finite temperature of the plasma. According to §3 in an earlier paper (Alfvén 1967), this effect is probably not of importance.

Considering Cassini's division as the cosmogonic shadow of Mimas, we find that the fall down ratio must be slightly higher than 1.5, in the environment of 1.55 (= 1/0.65). The deviation from the value 3/2 of the simple theory can be explained in two ways, either as an indirect effect of the production of a shadow, or as a temperature effect, with some preference to the first explanation. In contrast to this in the resonance theory of Cassini's division it is difficult to see why there should be any deviation from the theoretical resonance, which as mentioned is clearly outside Cassini's division.

7. The discovery of Janus

Recently a new satellite of Saturn has been discovered (Dollfus 1967). It has been called Janus and moves in an orbit with small excentricity at a distance of 2.65 times the equatorial radius of Saturn, which in the scale of Fig. 8 or 10 means at 22".0. It is about two magnitudes smaller than Mimas. This discovery makes it possible to check our earlier results.

If the resonance theory of Cassini's division is correct we should expect Janus to produce a resonance gap at $(0.5)^{2/3} = 0.63$ of its central distance which in the figure corresponds to 13.9. In this region of the luminosity curve there is not the slightest trace of any gap. If on the other hand the new satellite produces a cosmogonic shadow, this should be situated at $2/3 \cdot 22''.0 = 14''.7$. We find a clear minimum in the luminosity curve very close to the expected point. In fact the minimum in the figure is situated at $14''.6$, which with the orbital radius of Janus gives a fall down ratio of $1''.51$, slightly higher than the value of the simple theory and somewhat smaller than the value for Mimas-Cassini's division.

8. Prediction of a new satellite of Saturn

Between Cassini's division, identified as the cosmogonic shadow of Mimas, and the minimum at 14.6, identified as the cosmogonic shadow of Janus, there is another minimum, situated at 15.3. It seems possible that this should be connected with an undiscovered satellite of Saturn.

As the minimum is less pronounced than the Janus minimum, the undiscovered satellite should be smaller than Janus, perhaps by one magnitude. As the half-width of the minimum is similar to that of the Janus minimum, the excentricity of its orbit should be similar. This means probably that its orbit is almost circular.

The fall-down ratio for Janus is 1.51, whereas the ratio between Mimas' orbit and the centre of Cassini's division is 1.55. Interpolating between these two values we may expect the fall down ratio of the undiscovered satellite to be 1.52. This means that its orbital radius should be $1.52 \cdot 15.3 = 23.3$, corresponding to 2.80 equatorial radii of Saturn.

Hence we predict that there should be <u>an undiscovered satellite of Saturn moving in an almost circular orbit at 2.80 equatorial radii with a period of 19.5 hours</u>. It should be about one magnitude fainter than Janus.

9. <u>Prediction of a light maximum in the C-ring</u>

It seems also justified to make another prediction. As plasma accumulated in the region of the Cassini division has no grains which sweep it, it should fall down and form a weak luminous ring at 2/3 of Cassini's division. This means that there may be a light maximum in the C-ring in the region between $2/3 \cdot 16''.3 = 10''.9$ and $2/3 \cdot 15''.8 = 11''.2$ (marked by an arrow in Fig. 10). It would be of interest to look for this.

10. <u>Comment on the luminosity curve</u>

With our interpretation of the minima at 14.6 and 15.3 one may ask whether the sequence of minima near the outer edge of the A-ring and the double minima near the inner edge of the B-ring could indicate the existence of other undiscovered bodies. This is perhaps possible but not very likely. The regular sequence of maxima and minima at the outer edge of the A-ring gives more the impression of a damped oscillation, possibly associated with the rapid increase in density at the outer edge. The double minimum at the inner edge of the B-ring may have a similar explanation.

ACKNOWLEDGEMENT

Part of this research work was done while the author was a guest at the Institute for Advanced Study, Princeton, and in part it was done at the Space Sciences Laboratory, University of California, Berkeley, supported by the Office of Naval Research under contract Nonr 3656(26), and by the National Aeronautics and Space Administration under grants NsG 243 and NGR-05-003-230.

REFERENCES

Alexander, A. F., O'd. (1953). RAAF 64, 26.

Alexander, A. F. O'd. (1962). The Planet Saturn, London.

Alfvén, H., (1954). On the Origin of the Solar System. Oxford Univ. Press.

_________, (1962). On the mass distribution in the solar system. Astrophys. J. 136, 1005.

Alfvén, H. and Wilcox, J. M. (1962). On the origin of the satellites and the planets. Astrophys. J. 136, 1016.

Alfvén, H. and Fälthammar, C-G. (1963). Cosmical Electrodynamics, Fundamental Principles, Oxford Univ. Press.

Alfvén, H., (1963). The early history of the Moon and the Earth. Icarus 1, 357.

_________, (1963). On the early history of the Sun and the formation of the solar system. Astrophys. J. 137, 981.

_________, (1964). On the origin of the asteroids. Icarus 3, 52.

_________, (1964). On the formation of celestial bodies. Icarus 3, 57.

_________, (1965). Origin of the Moon. Science 148, 476.

_________, (1967). On the origin of the solar system. Harold Jeffrey's lecture at the Royal Astronomical Society, London, May 12, 1967. Monthly Notices 87, No. 960.

_________, (1968). Partial corotation of a magnetized plasma. Icarus (to be published).

_________, (1968). On the structure of the Saturnian rings. Icarus (to be published).

Colombo, G. and Shapiro, I. (1966). The rotation of the planet Mercury, Astrophys. J. 145, 296.

Cooper, J. A., Richards, J. R., and Stacey, F. C. (1967). Possible new evidence bearing on the lunar capture hypothesis, Nature 215, 1256.

Dessler, A. J. (1967). Solar wind and interplanetary field, Rev. Geophysics 5, 1.

Dole, S. H. (1962). The gravitational concentration of particles in space near the earth. Planet. Space Sci. 9, 541.

Dollfus, A. (1961). Visual and photographic studies of planets at the Pic du Midi. (Gerhard P. Kuiper and Barbara M. Middlehurst, The solar system, Chicago, Vol. III, p. 568.)

Dollfus, A. (1967). C. R. Acad. Sci. B 264, 822.

Gerstenkorn, H. (1955). Über Gezeitenreibung beim Zweikörperproblem. Z. Astrophys. 36, 245.

Gerstenkorn, H. (1967). On the controversy over the effect of tidal friction upon the history of the Earth-Moon-System. Icarus 7, 160. See also Ruskol, E. L. (1966). On the past history of the Earth-Moon-System. Icarus 5, 221.

Giuli, T. (1968). On the rotation of planets produced by gravitational collection of particles. To be published in Icarus.

Jeffreys, H. (1952). The Earth. The University Press, Cambridge.

Littleton, R. A. (1936). Monthly Notices Roy. Astron. Soc. 97, 108.

Lüst, R. and Schlüter, A. (1955). Drehimpulstransport durch Magnetfelder und die Abbremsung rotierender Sterne. Z. Astrophys. 38, 190.

MacDonald, G. (1964). Tidal friction. Rev. Geophys. 2, 467.

Olsen, W. (1966). Origin of the Cambrian-Precambrian unconformity. American Scientist 54, 458.

Persson, H. (1963). Electric field along a magnetic line of force in a low-density plasma. Phys. Fluids 6, 1756.

Persson, H. (1966). Electric field parallel to the magnetic field in a low-density plasma. Phys. Fluids 9, 1090.

Sorokin, N. A. (1965). Astron. Zh. 42, 1070.

FIGURE CAPTIONS

Fig. 1 Periods of axial rotation for the asteroids in relation to their masses. To the right are included the periods of the ordinary planets. (From H. Alfvén, Icarus 3, 52, 1964.)

Fig. 2 Particle orbits in a rotating coordinate system (according to Dole). Small bodies ("grains") which originally move in circular orbits around the sun with orbital radii greater than 1 A.U. will gradually be overtaken by the earth. In a rotating coordinate system which fixes the earth at the origin and the sun on the abscissa to the left at a distance of 1 A.U. (thus assuming the earth has a circular orbit), the particles will approach the earth and will move in the complicated trajectories depicted in the figure. If their original heliocentric orbital radii fall within seven ranges of values ("hands"), they will hit the earth. Otherwise, they will depart from the neighborhood of the earth and return to heliocentric (but non-circular) orbits. Seven similar hands exist for particles with initial orbital radii less than 1 A.U.

Fig. 3 Particles shot out tangentially with approximately the escape velocity from the point B at the earth's equator (at 0600 local time) with move in an ellipse with apogeum at A. The motion is disturbed by the Coriolis force and by the tidal effect from the sun.

Fig. 4 Particles originally moving in slightly eccentric Kepler ellipses in the solar field may hit the earth in two jets, both giving prograde rotation.

Fig. 5 Plasma in a magnetic dipole field from a rotating central body. A particle is acted on by the gravitation f_g which makes the angle α with the magnetic field, and by the centrifugal force f_c, which makes the angle $\lambda-\alpha$ with the magnetic field.

Fig. 6 Condensation of "grains" from a partially corotating plasma in the environment of Saturn.

The condensation is assumed to take place essentially from the neighborhood of the equatorial plane. The figure refers to a state when part of the plasma has already condensed so that Mimas and the rings are existing although with only part of their present masses. The upper part of the figure refers to the plasma which has not yet condensed.

The plasma near the orbit of Mimas condenses on this satellite, leaving the "Region swept by Mimas" void of plasma. Similarly the plasma in the region of the already existing A-ring (and B-ring) condenses directly on the grains of the ring.

When the grains produced by the condensation fall down to 2/3 of their original central distances the state depicted in the lower part of the figure is produced. Cassini's division derived from the region swept by Mimas. The C-ring has a reduced intensity because part of the plasma has condensed on the already existing grains of the A-ring.

Fig. 7 Number of asteroids, plotted as function of their semi-major axis a. In the asteroid belt Jupiter produces very pronounced resonance effects so that there are almost no asteroids with orbital periods equal to 1/2, 1/3, 2/5, etc. of Jupiter's period.

Fig. 7 (Cont'd) The state of a partially corotating plasma is depicted in the upper part of the figure. Grains condensing outside Jupiter's orbit are captured or disturbed by Jupiter. The result is that there are very few asteroids with $a > 2/3\ a_4$ (called "Jupiter's cosmogonic shadow"). Plasma condensing on already existing asteroids produce a low limit cut-off ("own cosmogonic shadow") of the asteroid distribution at 2/3 of the upper limit.

Fig. 8 Photometric curve of the Saturnian rings (according to Dollfus 1961). The abscissa gives the radial distance in seconds of arc for Saturn placed at 10 A.U. For a comparison with Fig. VI:3 in Origin of Solar System the abscissa should be multiplied by 2.10.

The top scale gives the orbital period of the particles. The periods which are integer fractions of the periods of the inner Saturnian satellites are marked. According to the resonance theory the structure of the rings should be produced by resonances with these satellites.

Fig. 9 Resonance gaps in the asteroid belt. Number of asteroids as function of the semi-major axis. The arrows mark the places where the period of an asteroid is 1/3 or 2/5 of the period of Jupiter.

Fig. 10 Cosmogonic effects in the ring system. Dollfus' photometric profile compared with Mimas orbital distance reduced by a factor 2/3 (or 0.65). Cassini's division may be the "cosmogonic shadow" of Mimas.

Fig. 10 (Cont'd)

In the left corner the photometric profile is turned upside down and reduced by the factor 2/3 ("own cosmogonic shadow"). The rapid drop in intensity between the B-ring and C-ring coincides with the beginning of this shadow.

Effect of the recently discovered Janus: If the resonance theory were correct we should expect a gap at 13'.9 (marked "1/2 resonance of Janus"), but this cannot be traced. On the other hand there is a light minimum close to 2/3 the orbital radius of Janus as expected from the cosmogonic theory.

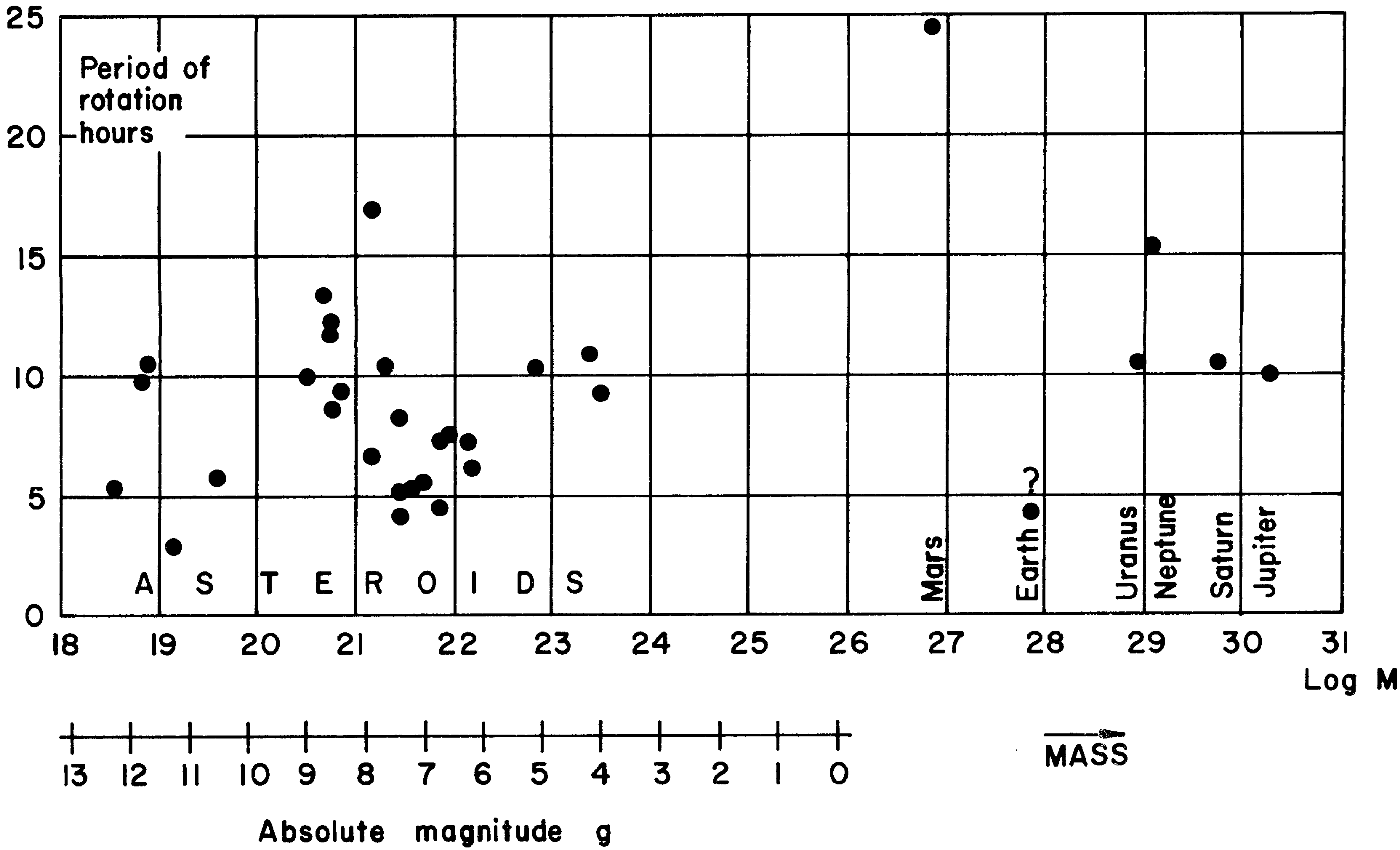
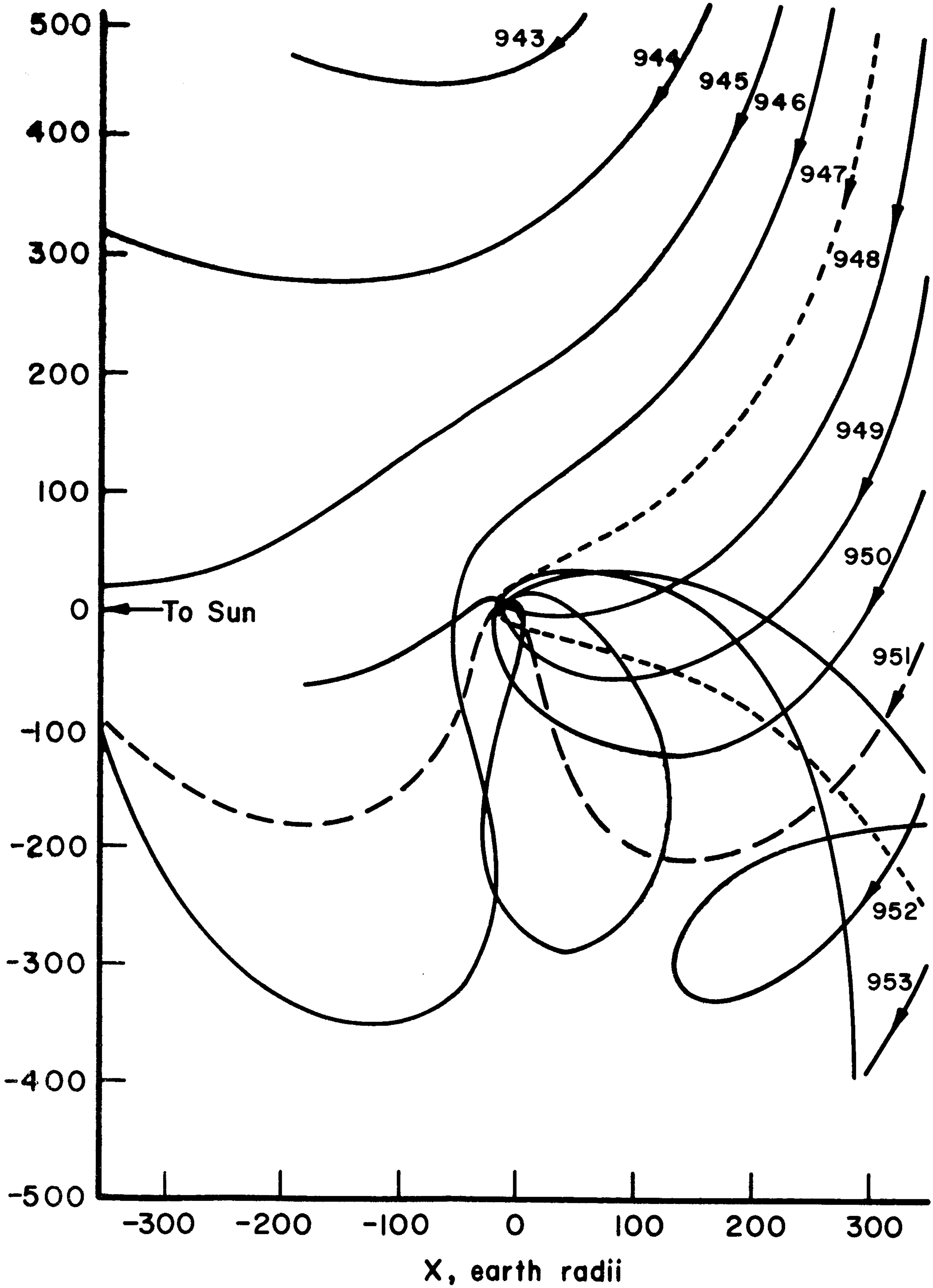

Period of
rotation
hours
25
20
15
10
5
0
A S T E R O I D S
Mars
Earth ?
Uranus
Neptune
Saturn
Jupiter
18 19 20 21 22 23 24 25 26 27 28 29 30 31
Log M
13 12 11 10 9 8 7 6 5 4 3 2 1 0
MASS
Absolute magnitude g

Figure 1



500
400
300
200
100
0
-100
-200
-300
-400
-500
-300
-200
-100
0
100
200
300
X, earth radii
To Sun
943
944
945
946
947
948
949
950
951
952
953

Figure 2

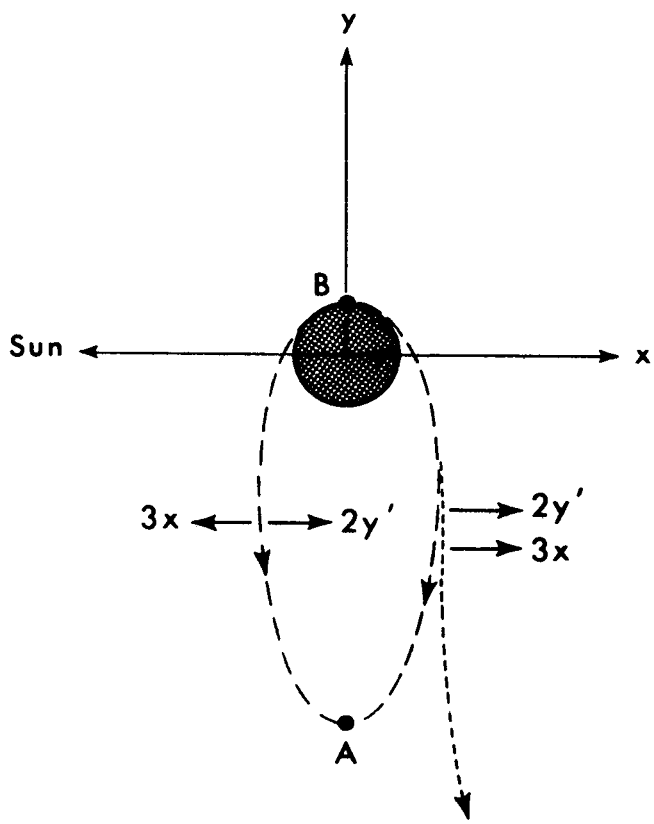


Figure 3

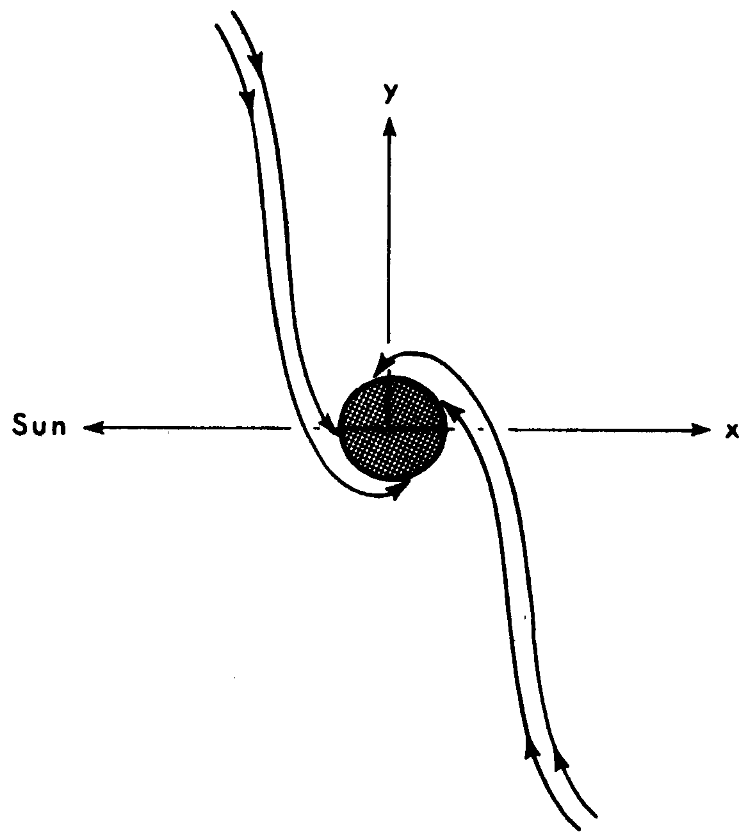


Figure 4

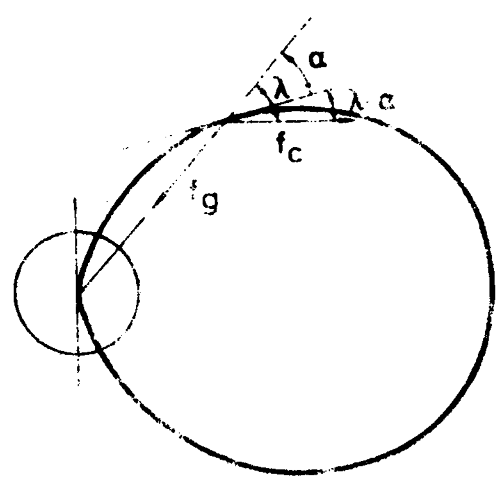


Figure 5

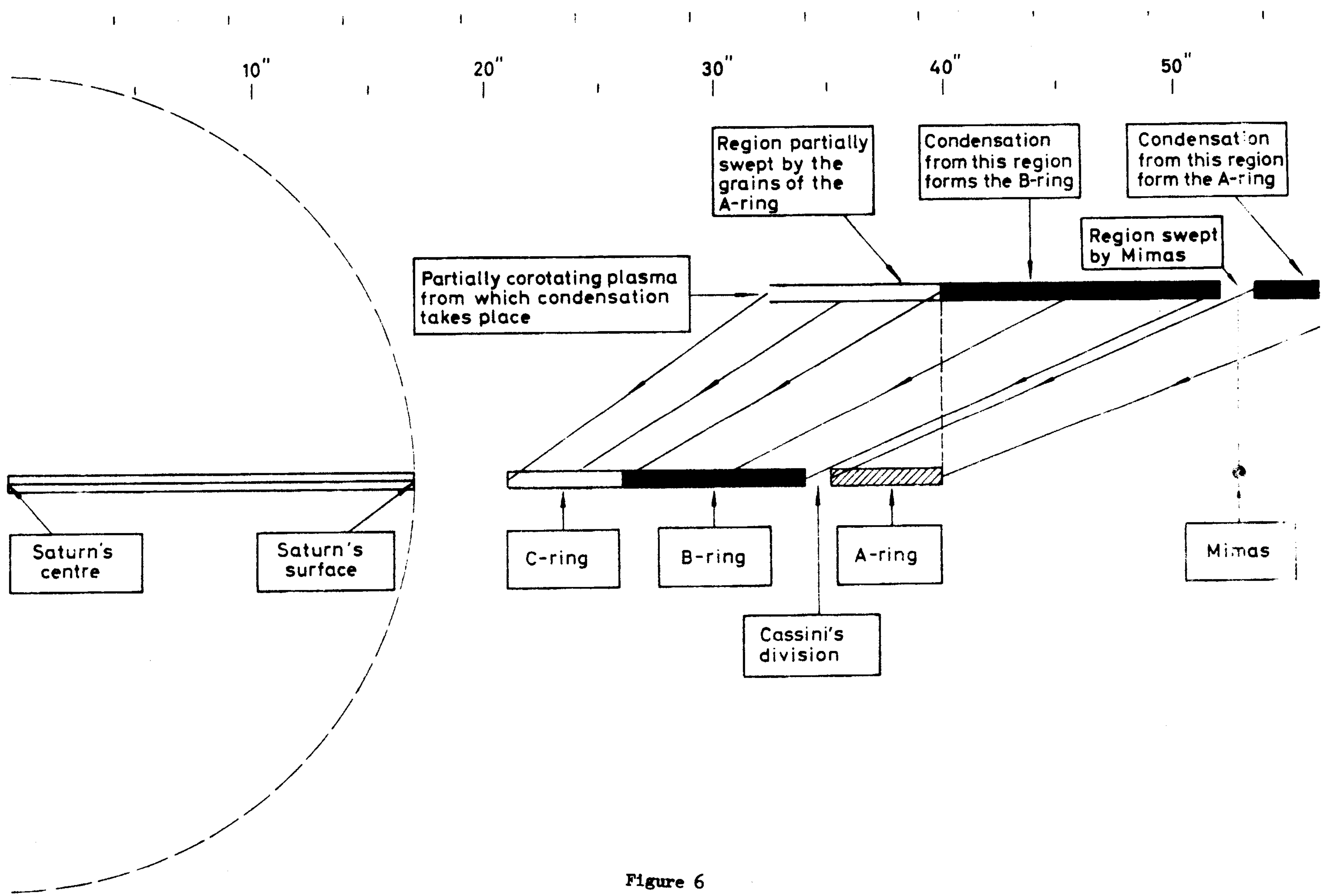
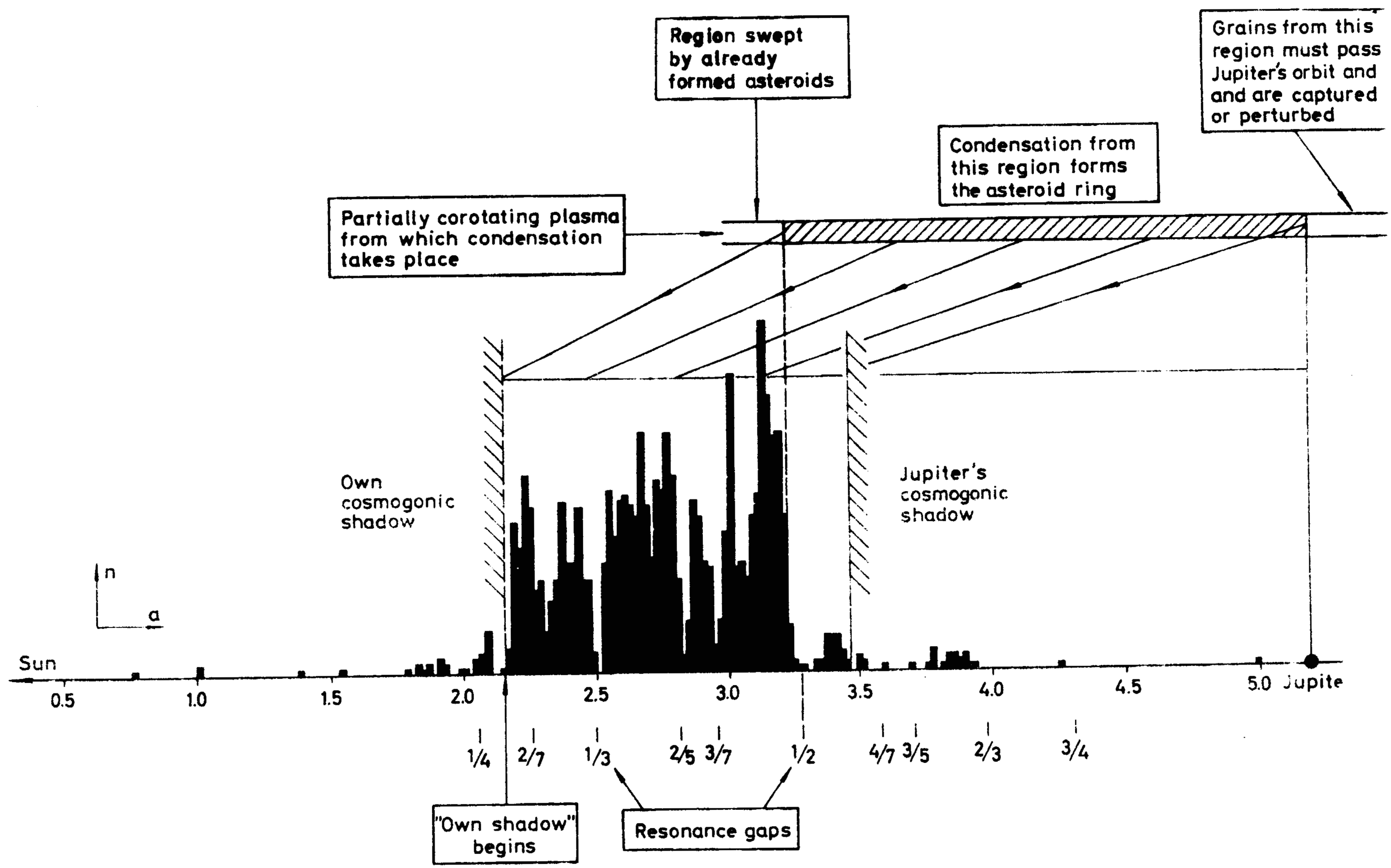
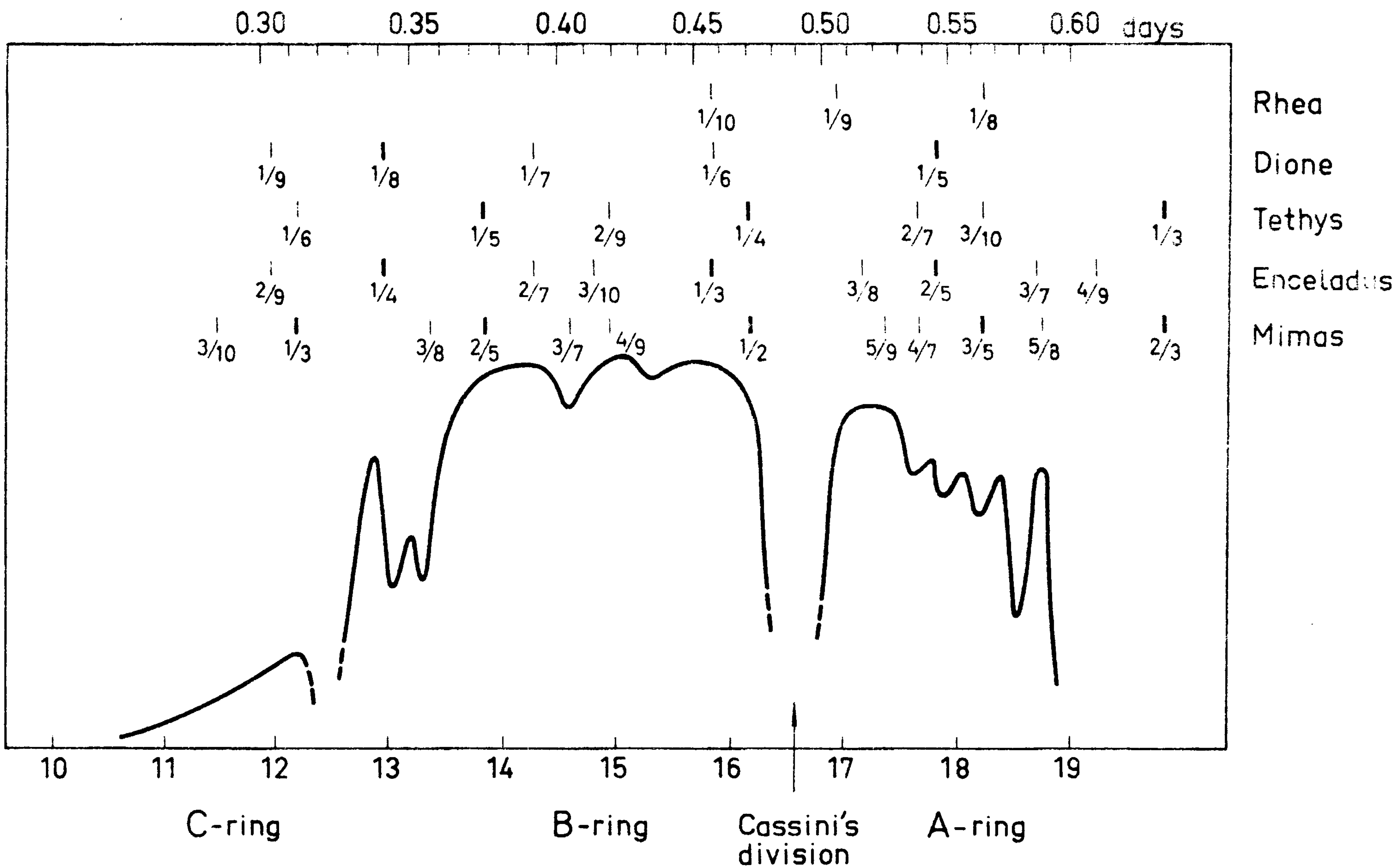

10"
20"
30"
40"
50"
Region partially swept by the grains of the A-ring
Condensation from this region forms the B-ring
Condensation from this region form the A-ring
Region swept by Mimas
Partially corotating plasma from which condensation takes place
Saturn's centre
Saturn's surface
C-ring
B-ring
A-ring
Mimas
Cassini's division

Figure 6



Region swept by already formed asteroids
Grains from this region must pass Jupiter's orbit and and are captured or perturbed
Condensation from this region forms the asteroid ring
Partially corotating plasma from which condensation takes place
Own cosmogonic shadow
Jupiter's cosmogonic shadow
n
a
Sun
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Jupite
1/4
2/7
1/3
2/5
3/7
1/2
4/7
3/5
2/3
3/4
"Own shadow" begins
Resonance gaps

Figure 7



0.30
0.35
0.40
0.45
0.50
0.55
0.60
days
Rhea
Dione
Tethys
Mimas
10
11
12
13
14
15
16
17
18
19
C-ring
B-ring
Cassini's division
A-ring

Figure 8

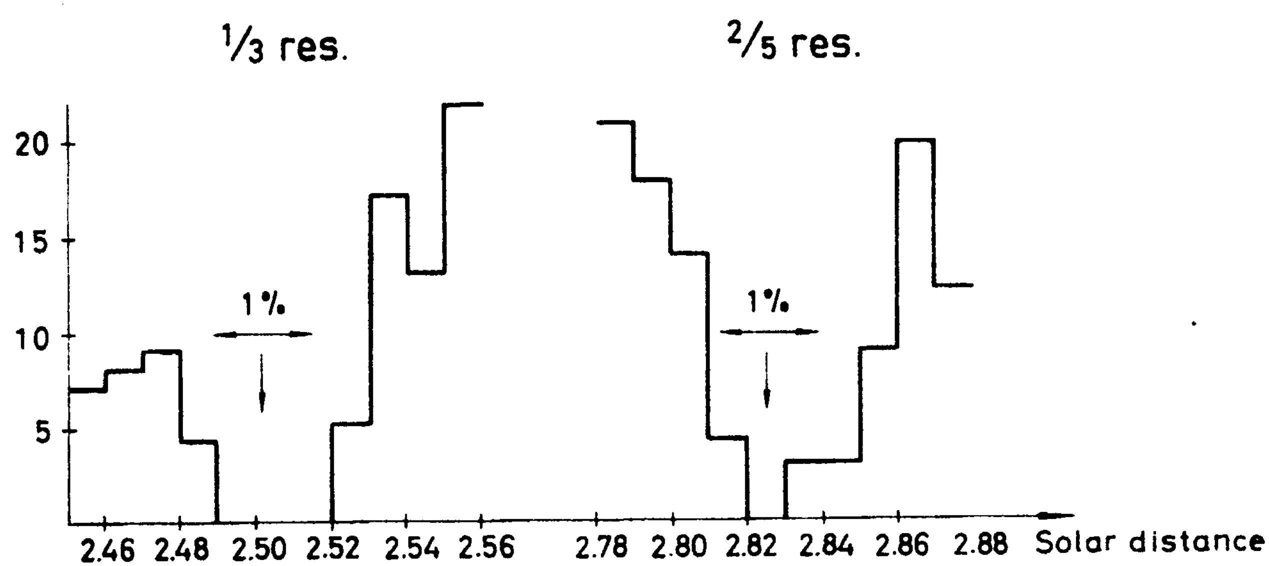
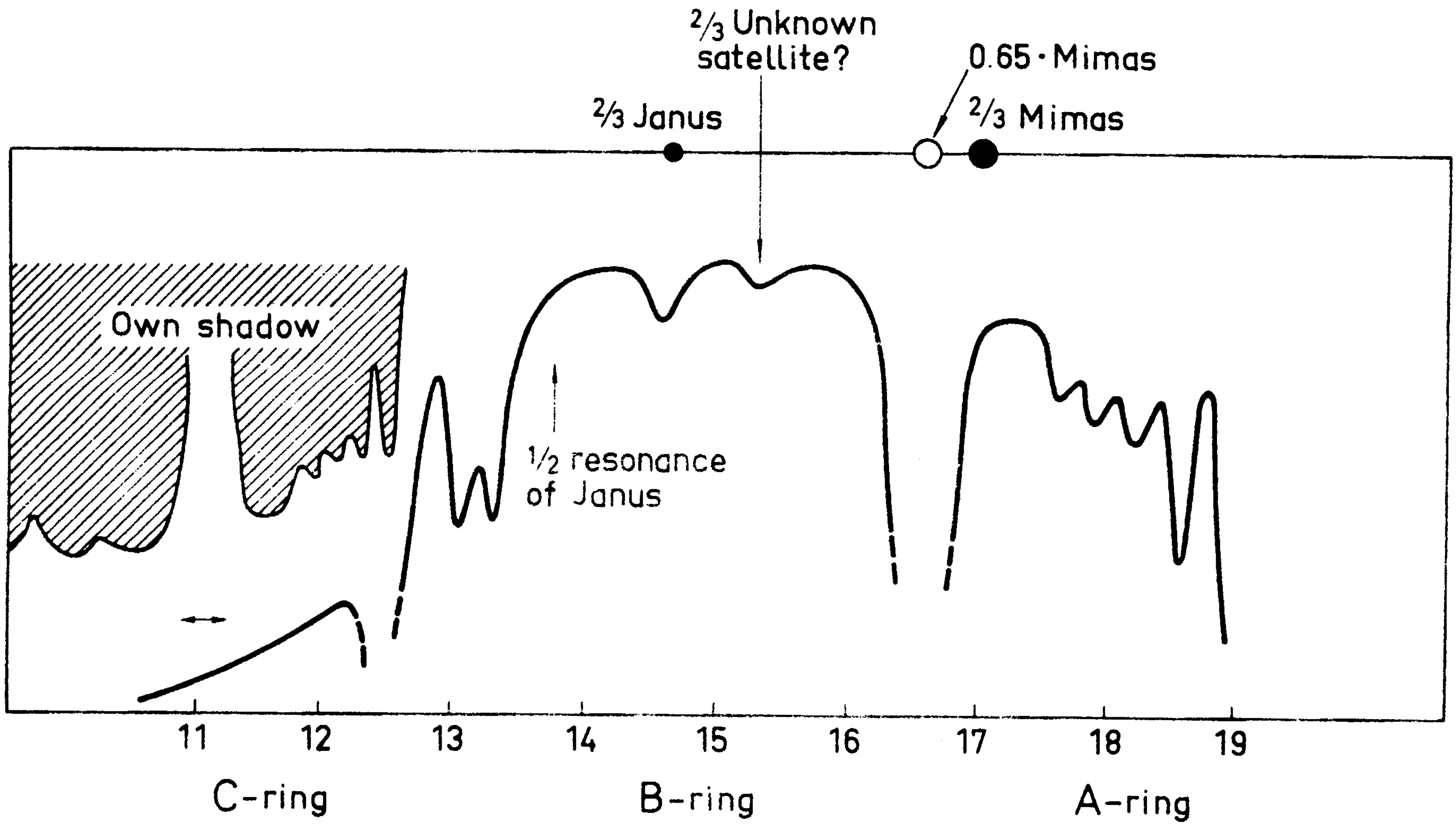

1/3 res.
2/5 res.
1 %
1 %
20
15
10
5
2.46 2.48 2.50 2.52 2.54 2.56
2.78 2.80 2.82 2.84 2.86 2.88
Solar distance

Figure 9



2/3 Unknown satellite?
0.65 · Mimas
2/3 Janus
2/3 Mimas
Own shadow
1/2 resonance of Janus
11
12
13
14
15
16
17
18
19
C-ring
B-ring
A-ring

Figure 10

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Space Sciences Laboratory
University of California
Berkeley, California 94720

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
ON THE ORIGIN OF THE SOLAR SYSTEM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (Last name, first name, initial)
Alfvén, Hannes

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November, 1967	65	31

8a. CONTRACT OR GRANT NO.
ONR Contract Nonr 3656(26)
NASA Grants Nsg 243 & NGR 05-003-230

b. PROJECT NO.

c. ONR proj. no. NR 021 101

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
Series 8, Issue 105

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Nuclear Physics Branch
Office of Naval Research
Washington, D. C. 20360

13. ABSTRACT

A theory of the origin of the solar system is discussed, including introduction and general principles, accretion of planets, partial corotation of a magnetized plasma, and the structure of the Saturnian rings. (U)

DD FORM 1 JAN 64 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cosmology						
Cosmogony						
Origin of solar system						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
__________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
__________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
__________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.